AIR WEATHER SERVICE
TECHNICAL REPORT 105-46

1613



# AIRCRAFT ICING OVER NORTHWEST EUROPE

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JULY 1945

HEADQUARTERS
AIR WEATHER SERVICE
WASHINGTON, D.C.

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HQ 21ST WEATHER SQUADRON

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# PROSPECTUS AND PRELIMINARY REPORT ON AIRCRAFT ICING OVER NORTHWEST EUROPE

PROSPECTUS:

This preliminary study of statistics on aircraft ice accretion over Northwestern Europe is the first in a series of proposed reports based on observational data taken by 9th Weather Reconnaissance Squadron (Prov). Flying P-51-B and P-51-D aircraft, this squadron completed 1340 successful tactical weather reconnaissance missions during the period 3 June 1944 to 3 May 1945. Their routes cover the English Channel, Southern North Sea, Northern France, the Low Countries and Germany west of 13°30' E; flights were made at average altitudes from 5000 to 15,000 feet, but frequently measurement of thick cloud decks took pilots as high as 30,000 feet and down to a few hundred feet above the ground. The large majority of these observations were made by experienced reconnaissance pilots and provide an accurate, detaild three-dimensional description of visual meteorological conditions over the area. Elements observed include measured altitudes of low and middle, estimated altitudes of high clouds, visibilities aloft and to the ground, precipitation, icing, turbulence and condensation trails.

The reconnaissance flights probide a unique source of data for meteorological research in sufficiently large quantities to insure moderate statistical accuracy. Several specific investigations have suggested themselves to the writer in addition to the present summary of icing statistics, which will be supplemented by a paper on the forecasting of aircraft icing in Northwestern Europe, describing icing conditions to be expected on the basis of synoptic situation, temperature lapse rate and similar information. Other among these topics are:

1. The relation between actual cloud structure and the elements of the radiosonde ascent, based on a large number of observations in close proximity to actual balloon runs.

2. The average structure of different types of fronts and frontal systems occurring over Northwest Europe.



Incl #3

3. The structure of decks of "North Sea stratocumulus" as related to the vertical distribution of temperature and moisture in the air mass.

4. The orographic effects of the mountains of Western Germany on different types of airflow.

5. A study of turbulence similar to the one on icing.

6. A study of condensation trails.

A considerable contribution to the accuracy of some of the above work can be gained by coordinating the observations of 9th Weather Reconnaissance Squadron (Prov) with higher level reconnaissance done over the same area by the Mosquito squadron of 325th Phot Reconnaissance Wing, Eighth Air Forces. Made principally between 20,000 and 30,000 feet, their flights can provide valuable information on altitudes of high cloud and tops of stronger frontal systems; they would similarly add much to any study of condensation trails or summer icing.

PRELIMINARY REPORT ON AIRCRAFT ICING
OVER NORTHWEST EUROPE:

The data presented below on aircraft ice accretion is the result of study of 1340 flights made by 9th Weather Reconnaissance Squadron (Prov) June 1944 to May 1945, of which 307 reported one or more instances of icing. Breakdown by seasons is presented; a further breakdown into months is not considered valuable, because the relatively small number of observations detracts from statistical accuracy.

Certain reservations must be made to the absolute accuracy of the figures on type and intensity of icing. These observations were made by experienced fighter pilots, flying aircraft which cruises at between 290 and 300 mph true airspeed. The icing usually occurred during a short period of flight in cloud or while ascending or descending. The intensities given are necessarily not based on any quantitative measurement of accretion and reflect, to the extent they have not been eliminatied by the writer, the biases of individuals. The only signigicant tendency, if any, is for pilots to overestimate the degree of icing. The intensities given conform fairly well to definitions appearing in Army Air Forces Training Manuals on aircraft icing: light icing is such that it can be readily handled by de-icing equipment but necessitates an eventual change of flight plan to avoid the condition, heavy icing is such that it cannot be hadled by de-icing equipment. However, the P-51 has no wing or propeller de-icers or anti-icers, and its only safe escape from hazardous icing is to climb or descend rapidly away from the condition. The German training manual Vereisung, D(Luft)1209 states that heavy icing is an increase in the ice coating of about one centimeter in five minutes, and this is as close to a quantitative estimate as we can come.

The greatest operational significance of the work of 9th Weather Reconnaissance Squadron (Prov) is that it was done entirely in single-engine fighter aircraft. An inordinate distrust of icing conditions seems to have grown up among many fighter pilots in the European Theater of Operations, even to the point of avoiding any instrument flight whatever. This fear was enhanced by the statement of theorists that ice accretion increases in direct proportion to airspeed, a claim which these observations tend partially to disprove. Desope these objedtions, pilots of the weather reconnaissance squadron flew instruments on more than 90 per cent of all their 1340 missions, yet only three cases occurred of an aircraft being forced to turn back or land because of icing. No losses or damage of planes have ever been even indirectly attributable to icing. Furthermore, substantially more cases of flight in cloud above the icing level without any icing at all were reported than cases with icing. Of all icing encountered, 85.6 per cent of the instances were light rime, light clear or moderate rime, types which by the statement of pilots themselves offer little or no hazard.

Certain general conclusions can be seiftly drqwn from the data presented below:

1. Icing is worst during Winter and Spring seasons, with maxima in November and January. Icing is an almost negligibel at altitudes from the surface to 15,000 feet during Summer months. This is partly because the clouds over Europe in Summer are largely convective type, is olated and easily avoided. Also the Summer of 1944 averaged considerably below the mean annual cloud cover.

2. Rime icing predominates in the ratio of five-to-one, and more dangerous clear icing is almost confined to cumulonimbus, bulging cumulus and nimbostratus (freezing rain) clouds. This is in agreement with theory that clear icing occurs only with large supercooled water droplets.

3. Rime icing is especially predominate in Winter, when strong convective clouds are rare over land.

4. In stratocumulus, altocumulus and middle type 7 (Ac and As) clouds, rime icing occurs almost exclusively (90-97 per cent), with innocuous light and moderate rime predominating in the last two.

5. Dangerous icing is almost a certainty above the freezing level in dumulonimbus, The icing danger in cumulus increases with the covective activity and attendant drop size.

6. There is only one chance in six of getting any icing in altostratus cloud, almost no chance in stratus, and less than a 50 per cent chance in stratocumulus, altocumulus and middle type 7. Flight through active altocumulus castellatus is responsible for the cases of moderate clear and heavy rime in altocumulus .

8. The cloud types in order of decreasing icing hazard are: cumulobimbus, nimbostratus (freezing rain), bulging cumulus, cumulus humilis, altocumulus, stratocumulus, middle type 7 (usually thin), altostratus and stratus. No icing is to be expected in the pure ice crystal (cirroform) clouds, excent in cumulonimbus anvil tops.

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TOTAL DATA (June 1944 - May 1945)

| | | |
|---|---|---|
| Total Missions: | 1340 | |
| Icing Reported: | 307 - | 22.9% |
| Uncertain: | 49 | 3.7% |
| No Icing: | 984 | 73.4% |

| | Light | Moderate | Heavy |
|---|---|---|---|
| Rime | | | |
| Clear | | | |

By Cloud Type:

| | St | Sc | Cu | Cb | Ns | As | Ac | M7 |
|---|---|---|---|---|---|---|---|---|
| Light Rime | 0 | 57 | 35 | 0 | 11 | 9 | 49 | 30 |
| Modt. Rime | 0 | 30 | 11 | 2 | 11 | 4 | 20 | 5 |
| Others:L.C | | 5 | 15 | 1 | | 2 | 5 | 1 |
| M.C | | | 10 | | 2 | 1 | 3 | |
| H.C | | | 3 | 2 | 3 | | | |
| H.R | | 5 | 8 | 2 | 3 | | 3 | 1 |

Times aircraft flew in cloud above freezing level without icing : 364

| Cloud Type : | St | Sc | Cu | Ns | Ac | M7 | As |
|---|---|---|---|---|---|---|---|
| Occurrences: | 8 | 114 | 19 | 3 | 88 | 47 | 85 |

| MONTH: | Jan. | Feb | Mar. | Apr. | May | June | July | Aug. | Sep/ |
|---|---|---|---|---|---|---|---|---|---|
| Total Missions: | 85 | 113 | 142 | 149 | * | 178 | 183 | 128 | 76 |
| Icing Reported: | 34 | 30 | 49 | 52 | | 13 | 7 | 3 | 9 |
| Percentage: | 40% | 27% | 35% | 35% | | 7% | 4% | 2.4% | 12% |

| Oct. | Nov. | Dec. |
|---|---|---|
| 59 | 94 | 122 |
| 18 | 37 | 47 |
| 31% | 39% | 38% |

SPRING (March, April, 1-3 May 1945)

| | | |
|---|---|---|
| Total Missions: | 302 | |
| Icing Reported: | 109 - | 36.1% |
| Uncertain: | 5 | 1.7% |
| No Icing: | 188 | 62.2% |

| | Light | Moderate | Heavy |
|---|---|---|---|
| Rime | 66 | 19 | 9 |
| Clear | 11 | 10 | 2 |

By cloud type:

| | St | Sc | Cu | Cb | Ns | As | Ac | M7 |
|---|---|---|---|---|---|---|---|---|
| Light Rime | 0 | 15 | 12 | 0 | 2 | 2 | 30 | 8 |
| Modt. Rime | 0 | 7 | 7 | 2 | 0 | 0 | 3 | 1 |
| Other: L.C. | | 2 | 7 | | | | 2 | |
| M.C. | | | 8 | | 1 | | 1 | |
| H.C. | | | | 1 | 1 | | | |
| H.R. | | 2 | 3 | 1 | 1 | | 1 | 1 |

Times aircraft flew in cloud above freezing level without icing : 83

| Cloud Type : | St | Sc | Cu | Ns | As | Ac | M7 |
|---|---|---|---|---|---|---|---|
| Occurrences: | 1 | 20 | 4 | 1 | 18 | 27 | 12 |

SUMMER (June, July, August 1944)

| | | |
|---|---|---|
| Total Missions: | 489 | |
| Icing Reported: | 23 - | 4.7% |
| Uncertain: | 29 - | 5.9% |
| No Icing: | 437 - | 89.4% |

| | Light | Moderate | Heavy |
|---|---|---|---|
| Rime | 11 | 7 | 0 |
| Clear | 2 | 1 | 2 |

By Cloud Type:

| | St | Sc | Cu | Cb | Ns | As | Ac | M7 |
|---|---|---|---|---|---|---|---|---|
| Light Rime | 9 | 6 | 3 | 0 | 2 | 0 | 1 | 1 |
| Modt. Rime | 0 | 1 | 0 | 0 | 4 | 1 | 1 | 0 |
| Other: L.C. | | | 2 | | | | | |
| M.C. | | | 1 | | | | | |
| H.C. | | | 1 | | 1 | | | |
| H.R. | | | | | | | | |

Times aircraft flew in cloud above freezing level without icing : 117

| Cloud Type : | St | Sc | Cu | Ns | As | Ac | M7 |
|---|---|---|---|---|---|---|---|
| Occurrences: | 2 | 23 | 6 | 2 | 37 | 32 | 15 |

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FALL (September, October, November 1944)

Total Missions: 229
Icing Reported: 64 - 28.0%
Uncertain: 4 - 1.7%
No Icing: 161 - 70.3%

| | Light | Moderate | Heavy |
|---|---|---|---|
| Rime | 31 | 14 | 4 |
| Clear | 12 | 2 | 3 |

By Cloud Type:

| | St | Sc | Cu | Cb | Ns | As | Ac | M7 |
|---|---|---|---|---|---|---|---|---|
| Light Rime | 0 | 10 | 8 | 0 | 2 | 3 | 5 | 5 |
| Modt. Rime | 0 | 4 | 0 | 0 | 5 | 0 | 6 | 0 |
| Other: L.C. | | 2 | 4 | 1 | | 1 | 3 | 1 |
| M.C | | | 1 | | | | 1 | |
| H.C. | | | 1 | 1 | 1 | | | |
| H.R. | | 1 | 1 | | 1 | | 1 | |

Times aircraft flew in cloud above freezing level without icing : 71

| Cloud Type : | St | Sc | Cu | Ns | As | Ac | M7 |
|---|---|---|---|---|---|---|---|
| Occurrences: | 0 | 28 | 3 | 0 | 20 | 17 | 3 |

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WINTER (December 1944, January, February 1945)

Total Missions: 320
Icing Reported: 111 - 34.7%
Uncertain: 11 - 3.4%
No Icing: 198 - 61.9%

| | Light | Moderate | Heavy |
|---|---|---|---|
| Rime | 68 | 33 | 10 |
| Clear | 5 | 3 | 1 |

By Cloud Type:

| | St | Sc | Cu | Cb | Ns | As | Ac | M7 |
|---|---|---|---|---|---|---|---|---|
| Light Rime | 0 | 26 | 12 | 0 | 5 | 4 | 13 | 16 |
| Modt. Rime | 0 | 18 | 4 | 0 | 2 | 3 | 10 | 4 |
| Other: L.C | | 1 | 2 | | | 1 | | |
| M.C. | | | | | 1 | 1 | 1 | |
| H.C. | | | 1 | | | | | |
| H.R. | | 2 | 1 | 1 | 1 | | 1 | |

Times aircraft flew in cloud above freezing level without icing : 93

| Cloud Type : | St | Sc | Cu | Ns | As | Ac | M7 |
|---|---|---|---|---|---|---|---|
| Occurrences: | 5 | 43 | 6 | 0 | 10 | 12 | 17 |

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s/Holt Ashley
t/HOLT ASHLEY
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TECHNICAL SECTION
HEADQUARTERS, 21ST WEATHER SQUADRON

18 July 1945

AIRCRAFT ICING OVER NORTHWEST EUROPE

Part I: Analysis of 1340 Weather Reconnaissance Flights, June 1944 - May, 1945.



A. General Remarks.

The data presented here on aircraft ice accretion are the result of a study of flights made by 9th Weather ?Reconnaissance Squadron (Prov), of which 307 reported one or more instances of icing. Flying P-51-B and P-51-D airplanes, this squadron completed 1340 succesful tactical weather reconnaissance missions during the period 3 June 1944 to 4 May 1945. Their routes cover the English Channel, Southern North Sea, Norther France, the Low Countries and Germany west of 13° 30' E. Flights were made at average altitudes from 5000 to 15,000 feet, but frequently measurement of thick cloud decks took pilots as high as 30,000 feet and down to a few hundred feet above the ground. The large majority of these observations were made by experienced reconnaissance pilots and provide a detailed three-dimensional dexcription of the visual meteorological conditions over the area covered. Elements observed include measured altitudes of low and middle, estimated altitudes of high clouds, visibility aloft and to the ground, precipitation, icing, turbulence and condensation trails.

It is felt that several limitations exist to the absolute accuracy and general usefulness of these icing data, and these should be listed before launching upon a detailed analysis:

a. The data are for a period of only one year. Although breakdown by seasons is presented, it is employed for statistical convenience rather than to emphasize differences. Thus, the total figures on icing related to fronts, cloud structure, etc, are more valuable than monthly or seasonal sums.

b. The pilots were not weather officers; although their experience level was high, their training was limited. At best, any icing observations will be affected by personal considerations and are not susceptible of quantitative measurement.

c. Only one type of aircraft was emploied. Experience with icing indicates considerable varation of intensity with the airfoil. This difference may be even more significant than the relative increase of ice accretion with increase in airspeed.[1]

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d. The high airspeed of the P-51 (290 to 300 true, cruising around 10,000 feet) and the natural desire to avoid icing situations combined to limit the time of flight in any particular condition. This rapid passage through cloud made good estimates of degree of icing very difficult. Also many pilots tend to overestimate icing as a result of early weather training.

To balance the above limitations, three facts tend to enhance the value of the data presented:

a. The large number of missions flown in approximately the same manner over the same area contributes the advantage of high statistical accuracy to the results. For exmaple, if all disturbing factors are eliminated aside from pure chance, the probable error in the chances of 307/1340 that any one such mission will encounter icing is less than four per cent.[2]

b. The pilots were all tranined in weather by the same personnel and according to the same outline. Standards of observation were passed from pilot to pilot by a process of having new men fly wing on their first missions. Only reliable, experienced pilots were permitted to lead flights regularly. Furthermore, the writer has tried to adjust some of the observations to a more level standard according to his personal experience with the pilots involved.

c. All missions were flown in the same type of aircraft, providing the results with internal continuity.

The greatest operational significance of the work of 9th Weather Reconnaissance Squadron (Prov) is that it was done entirely in singl-engine fighter aircraft. An undue fear of icing conditions seems to have grown up among many fighter pilots in the European Theater of Operations, even to the point of avoiding any instrument flight whatever.[3] Despite these objections, pilots of the weather reconnaissance squadron flew instruments on more than 90 per cent of all their 1340 missions, yet only three cases occurred of an aircraft being forced to turn back or land because of icing. No losses or damage of planes have ever been even indirectly attrivuted to icing. More cases occurred of flying in cloud above the freezing level withou icing than cases of icing. Of all icing encouterd, 85.6 per cent of the instances were light rime, light clear or moderate rime, types which by the statement of pilots themselves offer little or no hazard.

B. Analysis of Tables.

A number of general conclusions can swiftly be drawn from the tables presented below. Although many of these are obviou upon inspection, it is felt valuable to summarize them and point out, from experience, any especially significant or detracting factors involved. The reader is referred to the limitations set forth above as a deterrent from blind acceptance of these results as true in the general case.

From the data on total icing reported and icing by cloud type, the following facts are apparent:

a. The experiences of these pilots indicate that icing is worst during winter and spring months, with maxima in November, December and January. Icing is least prevalent, or rather most easily avoided, in summer.

b. Rime icing predominates in the ratio of five-to-one, and the more dangerous clear icing is almost confined to cumulonimbus, bulging cumulus and nimbostratus (freezing rain) clouds. This is in agreement with teory that clear icing occurs only with large supercooled water droplets.

c. Rime icing is especially predominate in winter, when strong convective clouds are rare over land away from immediate seacoasts.

d. In stratocumulus, altocumulus and middle type seven (Ac and As) clouds, rime icing occurs almost exclusively (90-97 per cent), with innocuous light and moderate rime prevailing in the last two.

e. Dangerous icing is almost a certainty above the freezing level in cumulonimbus; the icing danger in cumulus increases with the convective activity and attendant drop size.

f. There is only one case in six indicated here of getting icing in altostratus cloud, almost no chance in stratus, and less than a 50 per cent chance in stratocumulus, altocumulus and middle type seven(Ac and As). Flight through active altocumulus castellatus and cloud associated with spring and summer high level thunderstorm activity is responsible for the cases of moderate clear and heavy rime in altocumulus.

g. The cloud types in order of decreasing icing hazard are: cumulonimbus, nimbostratus (freezing rain), bulging cumulus, cumulus humilis, altocumulus, stratocumulus, middle type seven, altostratus and stratus. No icing is to be expected in the pure ice crystal (cirroform) clouds, except in cumulonimbus anvil topes.

From data on icing in fronts the following facts are apparent:

a. The experiences of these pilots indicate that there is no significant increase in the icing danger in frontal cloud over that in pure air mass cloud, except of course that the former is harder to avoid. Dangerous icing (heavy rime, moderate clear, heavy clear) was encountered in 16 per cent of the 116 cases in fronts; it was encountered in 14 per cent of the 210 cases in air mass cloud.

b. The greatest frontal icing danger occurs in two situations: in the overrunning cloud and attendant freezing rain of active warm fronts, and in the massed cumulonimbus and nimbostratus clouds of active cold front type occlusions.

c. No front may be safely assumed free of hazardous icing, except possibly inactive quasi-stationaries. Cold fronts encountered were less dangerous than warm and occluded types.

From the data on icing related to air mass the following facts are apparent:

a. The experiences of these pilots indicate a closer correlation between air mass type, the occurrence of icing, and the occurrence of hazardous icing.

b. Icing is almost limited to air masses of maritime origin, which predominate in a large ratio in Northwest Europe. This observation is in agreement with authors on the subject.[4]

c. Dangerous icing is present to a much higher degree in unstable air masses, with their associated strongly convective clouds. The largest fraction of cases of heavy rime, moderate clear and heavy clear is 25 out of 135 in unstable mPka; next comes unstable maritime tropical with eight out of 40; unstable mPwa (common over land in winter) is third with seven out of 45.

d. Rime icing is the normal situation in stable maritime air masses; only five cases of dangerous icing were reported out of 89 encounters in such air.

e. Icing in continental air was reported too infrequently to make generalizations. The case of heavy clear icing in unstable continental tropical of African origin occurred in an afternoon cumulonimbus. This air was modified by some addition of moisture during a short trajectory over the Mediterranean Sea.

f. The final subscripts in air mass designations are translated as follows: a, of Atlantic origin; b. of continental European origin; af, of African origin.

Some explanation of the table on icing related to stability and relative humidity is in order. For each case it was attempted to find the radiosonde[5] observation best representing the column of air in which the icing was encountered. The icing layer was then investigated to ascertain the avege relative humidity code figure, thus dividing the cases into classes of width ten per cent each below 90 per cent and five per cent each above 90 per cent. Secondly it was estimated whether the icing layer had an approximately moist adiabatic lapse rate, was definitely more stable, or definitely more unstable than moist adiabatic. From this data the following facts are apparent:

a. The experiences of these pilots indicate that, although saturated atmospheric layers of great instability are rare over Northwest Europe, where they do occure below freezing temperatures dangerous icing is almost a certainty.

b. Icing in definitely stable layers is usually not hazardous. Only four cases of dangerous icing occurred out of 67 flights in such air, all of them heavy rime.

c. Icing danger increases with higher relative humidity, as indicated by radiosonde observations. Dangerous icing is rare below 90 per cent; only light icing was met below 80 per cent.

In association with the radiosonde investigation, the teperature at which each case of icing took place was determined. The most interesting fact discovered is that of 47 cases of dangerous icing only five occurred at temperatures below -10° C. (14° F.). Of these cases, four heavy rime and one heavy clear, all but one were in strong convective cloud in an unstable maritime air mass. The heavy clear was met near -20° C. in cumulonimbus of an active cold front type occlusion. These facts confirm the statements of some authors regarding relative safety from dangerous icing at temperatures far below freezing.[6] Two cases of light rime were reported in stratocumulus overcasts at temperatures confirmed to be above freezing (between 0° and 2° C.). These offer proof of McNeal's suggestion[7] that light ice can occur through evaporational cooling in cloud up to about 35.6° F. Considering the high cruising speed of the P-51, they indicate that the assumption of an effective increase in the height of the freezing level due to dynamic warming of air passing over the wings is probably fallacious.[8]

C. Tables

TOTAL DATA (June 1944 - May 1945

| | | |
|---|---|---|
| Total Missions: | 1340 | |
| Icing Reported: | 307 | 22.9% |
| Uncertain: | 49 | 3.7% |
| No Icing: | 984 | 73.4% |

| | Light | Moderate | Heavy |
|---|---|---|---|
| Rime | 176 (54.0%) | 73 (22.4%) | 23 (7.1%) |
| Clear | 30 (9.2%) | 16 (4.9%) | 8 (2.4%) |

TOTAL DATA (continued)

By Cloud Type:

| | | St | Sc | Cu | Cb | Ns | As | Ac | M7 |
|---|---|---|---|---|---|---|---|---|---|
| Light Rime | | 0 | 57 | 35 | 0 | 11 | 9 | 49 | 30 |
| Modt. Rime | | 0 | 30 | 11 | 2 | 11 | 4 | 20 | 5 |
| Other: | L.C. | | 5 | 15 | 1 | | 2 | 5 | 1 |
| | M.C. | | | 10 | | 2 | 1 | 3 | |
| | H.C. | | | 3 | 2 | 3 | | | |
| | H.R. | | 5 | 8 | 2 | 3 | | 3 | 1 |

Times aircraft flew in cloud above
freezing level without icing : 364

| Cloud Type : | St | Sc | Cu | Ns | As | Ac | M7 |
|---|---|---|---|---|---|---|---|
| Occurrences: | 8 | 114 | 19 | 3 | 85 | 88 | 47 |

Icing not in Front: 210 (64.4%)

| | Light | Moderate | Heavy |
|---|---|---|---|
| Rime | 113 | 48 | 15 |
| Clear | 21 | 11 | 2 |

Icing in Front: 116 (35.6%)

| | | L.R. | M.R. | H.R. | L.C. | M.C. | H.C. | Total |
|---|---|---|---|---|---|---|---|---|
| Weak | C.F. | 9 | 7 | 0 | 1 | 1 | 0 | 18 |
| Modt. | C.F. | 10 | 2 | 0 | 4 | 1 | 1 | 18 |
| Strong | C.F. | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| Weak | W.F. | 17 | 4 | 4 | 0 | 0 | 0 | 25 |
| Modt. | W.F. | 11 | 1 | 2 | 2 | 2 | 2 | 20 |
| Strong | W.F. | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| Weak | Occ. | 4 | 4 | 1 | 0 | 1 | 0 | 10 |
| Modt. | Occ. | 8 | 6 | 1 | 1 | 0 | 1 | 17 |
| Strong | Occ. | 0 | 0 | 0 | 0 | 0 | 2 | 2 |
| Stationary | | 3 | 0 | 0 | 1 | 0 | 0 | 4 |
| Total: | | 63 | 25 | 8 | 9 | 5 | 6 | 116 |

Dangerous Icing Cases below $-10^{\circ}$ C.: 6 out of 47 (13%)

| Heavy Rime | Modt. Clear | Heavy Clear |
|---|---|---|
| 5 | 0 | 1 |

TOTAL DATA (continued)

Probable Air Mass:

| | | L.R. | M.R. | H.R. | L.C. | M.C. | H.C. | Total |
|---|---|---|---|---|---|---|---|---|
| Unstable | mPka | 70 | 28 | 13 | 12 | 9 | 3 | 138 |
| Stable | mPka | 10 | 5 | 0 | 2 | 0 | 0 | 17 |
| Unstable | mPwa | 20 | 13 | 6 | 5 | 1 | 0 | 45 |
| Stable | mPwa | 41 | 18 | 2 | 4 | 3 | 0 | 68 |
| Unstable | mT-a | 21 | 8 | 2 | 3 | 2 | 4 | 40 |
| Stable | mT-a | 3 | 0 | 0 | 1 | 0 | 0 | 4 |
| Unstable | cPke | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| Stable | cPke | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| Unstable | cPwe | 3 | 0 | 0 | 0 | 1 | 0 | 4 |
| Stable | cPwe | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| Unstable | cTwaf | 3 | 1 | 0 | 0 | 0 | 1 | 5 |
| Stable | cTwaf | 4 | 0 | 0 | 1 | 0 | 0 | 5 |
| Total: | | 176 | 73 | 23 | 30 | 16 | 8 | 326 |

Icing Related to Radiosonde: 228 (November 1944 - May 1945)

| | L.R. | M.R. | H.R. | L.C. | M.C. | H.C. | Total |
|---|---|---|---|---|---|---|---|
| M.A. | 0 | 1 | 4 | 1 | 5 | 1 | 12 |
| M.A. | 85 | 34 | 9 | 11 | 9 | 1 | 149 |
| M.A. | 42 | 18 | 4 | 3 | 0 | 0 | 67 |
| R.H. 0 | 43 | 19 | 9 | 7 | 9 | 2 | 89 |
| R.H. 9 | 56 | 28 | 6 | 6 | 4 | 0 | 100 |
| R.H. 8 | 22 | 6 | 2 | 1 | 1 | 0 | 32 |
| R.H. 7 | 4 | 0 | 0 | 1 | 0 | 0 | 5 |
| R.H. 7 | 2 | 0 | 0 | 0 | 0 | 0 | 2 |
| Total: | 127 | 53 | 17 | 15 | 14 | 2 | 228 |

| MONTH: | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Total Missions: | 85 | 113 | 142 | 149 | * | 178 | 183 | 128 | 76 | 59 | 94 | 122 |
| Icing Reported: | 34 | 30 | 49 | 52 | | 13 | 7 | 3 | 9 | 18 | 37 | 47 |
| Percentage: | 40% | 27% | 35% | 35% | | 7% | 4% | 2.4% | 12% | 31% | 39% | 38% |

*Only 11 missions flown.

SPRING (March, April, 1-3 May 1945)

Total Missions: 302
Icing Reported: 109 - 36.1%
Uncertain: 5 - 1.7%
No Icing: 188 - 62.2%

| | Light | Moderate | Heavy |
|---|---|---|---|
| Rime | 66 | 19 | 9 |
| Clear | 11 | 10 | 2 |

Times aircraft flew in cloud above freezing level without icing : 83

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SUMMER (June, July, August 1944)

Total Missions: 489
Icing Reported: 23 - 4.7%
Uncertain: 29 - 5.9%
No Icing: 437 - 89.4%

| | Light | Moderate | Heavy |
|---|---|---|---|
| Rime | 11 | 7 | 0 |
| Clear | 2 | 1 | 2 |

Times aircraft flew in cloud above freezing level without icing :117

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FALL (September, October, November 1944)

Total Missions: 229
Icing Reported: 64 - 4.7%
Uncertain: 4 - 5.9%
No Icing : 161 - 89.4%

| | Light | Moderate | Heavy |
|---|---|---|---|
| Rime | 31 | 14 | 4 |
| Clear | 12 | 2 | 3 |

Times aircraft flew in cloud above freezing level without icing : 71

WINTER (December 1944, January, February 1945)

Total Missions:
Icing Reported: - 34.7%
Uncertain: - 3.4%
No Icing: - 61.9%

| | Light | Moderate | Heavy |
|---|---|---|---|
| Rime | 68 | 33 | 10 |
| Clear | 5 | 3 | 1 |

Times aircraft flew in cloud above
freezing level without icing : 93

Part II: The Forecasting of Aircraft Icing.

Aircraft ice accretion is the greatest weather hazard to regularly scheduled flight operation. Its primary danger does not lie, as blieved by many, in the widespread occurrence of icing in dangerous form, but rather in the difficulty of accurately forecasting the type and degree to be expected.

Part II of this study has been prepared to supplement and integrate the objective results on icing presented in Par I. The conclusions drawn herein are based in part on the writer's experience in ice forecasting for Northwest Europe, in part on facts and suggestions obtained from discussions and reading on the subject and in part on the material summarized in Part I.

The basic problem of an icing forecast is twofold: first, where in the atmosphere will water clouds or precipitation occur at temperatures below approximately 0° C.? second, what will be the range of droplet sizes and the total quantity of condensed moisture in these clouds? The first answer establishes the possibility of an icing situation, the second gives a good indication of whether or not the icing actually will occur and what will be its type and degree. The problem of cloud and temperature forecasting is a common and general one, so one must concentrate on the more difficult second question to forecast icing. In general, with a given type of aircraft, the degree of icing(light, moderate, heavy) will vary directyly with the quantity of condensed moisture per unit volume; the type (rime, clear) will depend on the predominant droplet size. The larger the droplets, the more likely they are to break on impact with the aircraft and form clear icing. To avoid non-essentials, the problems of usually light frost and rare melting-snow ice will be omitted; also it is assumed that the reader realizes rime and clear icing can exist in all degrees of combination.

The drop size in a given cloud depends on the strength of vertical currents available to support larger drops and on the length of time the cloud has existed. The quantity of condensed moisture depends, among other complex factors, on the temperature and the length of time a source of fresh moisture or added condensation has been able to feed additional or larger drops into the cloud. Thus it is seen that old and actively convective clouds are theoretically the source of most dangerous aircraft icing.

Such is the case in Northwest Europe, and two general synoptics situations often occur in which such bad icing may be expected:

a. During the winter half-year (October through March) with a west-northwest to northerly flow of cold unstable maritime air across the North Sea, a mass of active cumulus and cumulonimbus clouds, extending with strong convection to heights of 15,000-25,000 feet, is built up. Such clouds appear to reach 300 miles inland during the day before losing most of their intensity. Often such an air mass has already had a long trajectory across the North Atlantic Drift before reaching the added convective impulse of the relatively warm North Sea. These clouds are hard to avoid, particularly at night, and are usually a source of heavy rime and/or dangerous clear icing above their very low freezing levels.

b. During the late spring and summer months (April through August), a protracted southwest to south-southeasterly flow floods Northwest Europe with a mass of very warm, fairly stable air, always tropical in origin and subject to varying degrees of maritime influence. With the approach of a low from the west or southwest such air undergoes a decrease of stability, which progresses from high level down to the surface where it is greatly enhanced by afternoon heating from the strong seasonal insolation. With the approach of a fast-moving cold front (or cold front type occlusion) from the northwest, the convective instability of the tropical air is violently released. In either case, that of the low or that of the cold front, the result is the formation first of alto cumulus castellatus, then of strong cumulonimbus clouds and thunderstorms. Such clouds do not have the age vut they definitely have the c onvetion to produce very dangerous icing. The air mass cumulonimbus are fairly easily avoided in daylight; the cold-frontal cloud wass is almost impossible to avoid in flight, and severe turbulence renders such a situation dangerous even below the freezing level.

The one important source of dangerous icing which does not depend on convection and to produce it. The fact is that strong air mass discontinuities and sharp frontal inversions are very rare in Europe. However, freesing rain or glaze situations sometimes occur over small areas. The conditions are a southwesterly or southerly flow of maritime of continental polar air overrun by maritime tropical air from a warm front or occlusion approaching from a westerly quadrant or from waves forming on a quasi-stationary in the area. The worst icing is moderate or heavy clear and is nearly always met within the overrunning mT rather than below the frontal inversion. Often the release of convective instability in the mT is a contributing factor. In all the above forecasting it must be borne in mind that orographic influences always increase icing danger.

Before continuing a discussion of synoptic situations, some remarks are in order about the temperature effect on icing intensity. As we pointed out in Part I, except in actively convective clouds hazardous icing is a rarity below $-10^{\circ}$ C. The most dangerous cases of such convective cloud formation have been mentioned above; anyforecaster can recall a few others after a study of European weather. Excluding these situations, some interesting conclusions can be drawn concerning layers of icing hazard. Assuming a moist adiabatic lapse rate in cloud the layer from $0^{\circ}$ to $-10^{\circ}$ C. ranges around4500-5500 feet in thickness. This means that in a large majority of cases the layer of dangerous icing is less than 5500 feet thick. In strong warm-frontal overrunning, such as that described above, the lapse rate is much stabler than moist adiabatic, and the dangerous icing layer may be up to 10,000 feet thick. In other situations where cloud occurs in air more stable than moist adiabatic, observations such as those in part one demonstrate that little or no icing is usually the case. Thus an airplane with a good rate of climb can very often ascend rapidly through the icing layer without gathering a dangerously thick coating. This brings us to a very important principle: it is more fruitful in the long run to be able to forecast with assurance the absence of dangerous icing or the manner of avoiding it, than it is to be prepared with an ominous warning every time ther is the slightest possibility of such a hazard.

With that thought in mind, the following summary is presented of certain synoptic and cloud situations when icing is not the hazard it is believed bt some to be:

a. Often during the winter half-year the same sort of northerly to westerly flow of cold air as described above occurs onto the European continent from the North Sea, except that the air is under anticyclonic influence and exgibits subsidence and a definite dry inversion somewhere between 4000 and 10,000 feet. The normal situation here is an overcast of stratus or stratocumulus cloud. It is often in two distinct layers, but the total vertical thickness is seldom more than 5000 feet. If the trajectory has been westerly enough to pass over England or the French peninaulas the stratocumulus is broken. The usual icing condition is innocuous light or moderate rime. With layers less than 1500 feet thick ther is rarely ant icing at all. It is the writer's belief that cases of heavy rime reported in this cloud are caused by protracted flight in it, which permits considerable accumulation. Occasionally the problem is complicated by the presence of a few cumulus columns inside the stratocumulus, where the icing is locally more severe.

b. Throughout the year many cases occur in Northwest Europe of weak stationary fronts and the passage of dissipating ends of warm and occluded fronts. These are accompanied by little or no precipitation. They consist of many relatively thin, broken layers of stratocumulus and altocumulus, often with altostratus or haze between layers. Except in very isolated patches of freezing rain, these fronts do not constitute a source of hazardous icing. The maximum forecast should be for moderate rime, with no icing at temperatures below $-15^{\circ}$ C.

c. Throughout the year scattered to broken cumulus humilis and small bulging cumulus very frequently form between 1100 and 1900 hours in various maritime air masses. The dangerous icing in these clouds is confined to their tops, especially with a fairly high freezing level. In these tops it is usually moderate clear, heavy rime or mixtures. The forecast should be to avoid the cumlus topes, which is easily done. Even with isolated towering cumulus and cumulonimbus daylight flights can be cleared perfectly safely with this warning.

Finall , the following common cloud situations are mentioned, in which most forecasters will agree the icing hazard is small to negligible:

a. Throughout the year and with almost any wind direction, covergence and radiation effects combine to produce various thin scattered or brokendecks of str tus, stratocumulus, altostratus or altocumulus. Individual layers are rarely more than 2000 feet thick. The normal forecast is for light rime icing above the freezing level. In well over 50 per cent of such cases there is no visible icing at all.

b. On fall and winter mornings with or without snow cover patches or layers of persistent fog or stratus form as the result of nighttime radiation through clear air. Under freezing temperatures such a situation is not productive of icing. It is the writer's belief that isolated reports of take-off difficulties in such weather are explained by inadequate measures for prevention and removal of frost, which forms during the night on wings and other exposed surfaces.

It must be noted that many important cloud and synoptic situations have certainly been omitted from the above. The forecasters are referred to the general remarks made in the first four paragraphs. The primary sources of icing danger are active convection and extensive areas of freezing rain.

To conclude, the succesful icing forecaster is the man who can tell a pilot with equal confidence where icing is and where it is not a hazard.

Notes:

1. E.g.: B-26 aircraft flying at much lower airspeeds have often encountered moderate or severe icing in clouds where P-51 pilots reported only light rime. By expansion on material in Air Ministry Meteorological Office M.OM. 393, Notes for the Guidance of Forecasters ...... Ice Accretion on Aircraft, and approximate formula for the rate of ice accretion is:

$$1. \quad A. = KvEr \times \left[\frac{600 - t}{680}\right]$$

where v is the true airspeed, E the quantity of liquid water in unit volume of air, r the radius of water droplets and t the Centigrade temperature, all in c.g.s. units. The constant

K depends principally on the type of airfoil and little is known theoretically or experimentally about its values. From qualitative results, K is much lower for the P-51 than for the B-26.

2. C.H. Richardson, An Introduction to Statistical Analysis, USAFI, 1944 gives the following formula for the standard deviation from the mean of probabilities, assuming a point binomial curve is applied to the probabilities from a large number of series of n observations each:

$$\sigma = \sqrt{npq}$$

where n is the number of observations in each sample, and p and q are the respective probabilities that the event will or will not occur. For out observation series here: n 1340 p 307/1340, q 1033/1340;

$$\sigma = \sqrt{\frac{1340x307x1033}{1340x1340}} = 15.4$$

E .6745 10.4

The probable error E 10.4 cases of icing. The percentage probable deviation from the assumed mean of 307 is therefore E/M 10.4/307 3.4%.

3. Air Ministry Meteorological Office M.OM. 393 and other texts state that ice accretion is proportional to the true airspeed (see formula in footnote 1.). P-51's slying at cruising speeds of 290 to 310 mph did not gather ice in large enough quantities to offer any proof of this contention. Comparisions of P-51, B-26 and A-26 icing hint that the icing may be much more influenced by the character of the airfoil above 200 mph.

4. George F. Taylor, Aeronautical Meteorology: New York, 1942, states:

"...severe icing in air of continental extraction is very rare. . . .Any unstable layers in an air mass of recent maritime extraction associated with temperatures below the freezing point is sufficient indication for moderate or severe icing conditions."

5. Nearly all the radiosonde instruments were Friez or Washington Institute of Technology variable audio-frequency type, with plastic temerature and chemical relative humidity elements.

6. Air Ministry Meteorological Officer M.OM. 393 states:

"At temperatures below 15° F. serious ice accretion is mainly limited to convectional clouds."

In contrast, Taylor, op. cit, warns:

"It has frequently been states that rime icing occurs at very low temperatures and that clear icing is only found at temperatures above about 20° F. This assumption is wholly unfounded and cases of severe clear icing have many times been reported at temperatures well below 0° F."

7. Don McNeal, Ice Formation in the Atmosphere: Jour. Aero. Sci., v. 4, n. 3, 1937

8. The German training manual Vereisung, D(Luft)1209: Berlin, 1940, gives the following table of effective rise in the freezing level due to dynamic heating:

| Airspeed | Increase in F. L. |
|---|---|
| 200 km/hr | 150 m. |
| 300 | 300 |
| 400 | 500 |
| 500 | 800 |
| 600 | 1200 |
| 700 | 1600 |
| 800 | 2100 |

The relationship is assumed to be of the theoretically correct form $T = Kv^2$, where T is the dynamic temperature increase and v the airspeed.

9. Air Ministry Meteorological Office M.O.M. 393 states: "In the British Isles true rain ice is very rare." "On the European continent ..... rain ice is not so rare,"

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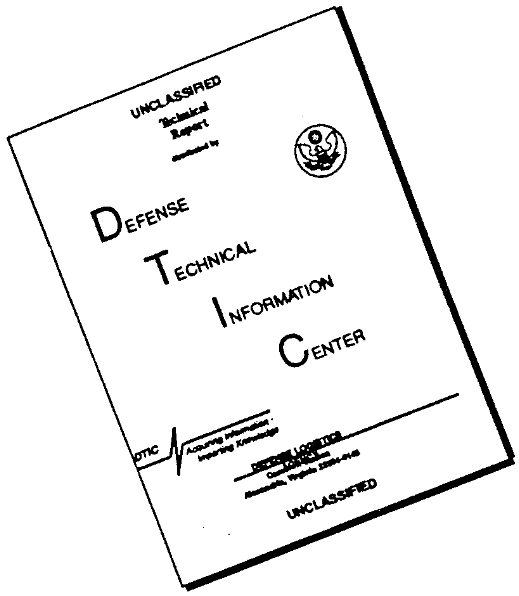


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